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Dual stable isotope tracing the source and composition of POM during algae blooms in a large and shallow eutrophic lake: All contributions from algae?

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A R T I C L E I N F O

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A B S T R A C T

Particulate organic matter (POM) plays an important role in biological pumping as a source of energy and nutrients in aquatic systems, as well as being the mechanism for algal bloom formation. However, research on its sources and composition, particularly the research on the contribution of algae in the bloom season, is still insufficient. In this study, the sources and composition of the POM in the surface water of Lake Taihu during the algal bloom season were quantitatively analysed. Dual stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes revealed that the algae were not the only sources of POM during algal blooms, and their contributions were inconsistent in the different lake regions. On average, algae made up 57.2% of the POM in Lake Taihu. Due to wind farms and nutrient runoff, algal POM was mainly concentrated in Meiliang Bay, Gonghu Bay and Central Taihu. The proportions of algal POM in the western estuary area and East Taihu were the smallest with a minimum of 10.8%. The proportion of terrestrial POM in the surface water and vertical sections was 18.3% and 40.0%, respectively. Furthermore, the highest value was 76.8%, which accounted for a large proportion in the algal bloom season. The terrestrial POM that came from rivers was mainly concentrated in the western part of Lake Taihu, while the resuspension of sediments also increased the proportion of terrestrial sources in the surface water. Affected by the distribution of the vegetation in Lake Taihu, the proportion of macrophyte POM in East Taihu was higher than that of algal sources. Although the contribution of endogenous POM might further increase due to the dual effects of climate change and eutrophication, our isotopic evidence suggested that terrestrial POM cannot be ignored, even in the algal bloom season.

1. Introduction

Particulate organic matter (POM) is a dynamic reservoir of organic matter in lakes that can impact the food chain, productivity and the fate of trace contaminants in lake environments (Mccusker et al., 1999; Ostrom et al., 1998). The POM in lakes is composed of a variety of colloidal and particulate matter, including living and nonliving material from internal and external sources (Derrien et al., 2017; Nienhuis, 1981). All sources of POM represent a complex mixture of biogenic reactivity and reflect the short-term nutrient fluctuations in the water column (Cao et al., 2016). The estimation of POM sources is critical to providing sufficient resolution data for understanding the material migration and transformation in lake biogeochemical processes.

Currently, it is generally accepted that lake organic matter from autochthonous sources that is produced in situ by photoautotrophic phytoplankton and hydrophytes and allochthonous matter is delivered through river discharge and runoff (Meyers and Ishiwatari, 1993). In eutrophic waters, algal blooms frequently occur (Biggs, 2000), and dense cyanobacterial blooms result in more POM in water (Shi et al., 2018). The positive correlation between the phytoplankton biomass, chlorophyll concentration, number of algae cells, organic carbon concentration and POM is often used to determine whether algae are the source of POM (Bowszys et al., 2014; Gobler and Sanudo-Wilhelmy, 2003; Zhang et al., 2018). However, in large shallow lakes, the input of exogenous organic matter from connecting river networks may also be a crucial contributor to POM. For instance, Lake Taihu, China has received large amounts of untreated effluents and soil runoff from rivers and has suffered from eutrophication since the 1990s (Hu et al., 2006).

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More than 200 rivers empty into Lake Taihu, and algal ecotypes coexist with grassy ecotypes (Qu et al., 2011), which makes the spatial distribution of the water quality in Lake Taihu more varied. Moreover, the water exchange period in Taihu Lake is only 300 days, and the terrestrial POM may occupy a large proportion of the lake. With the increase of human activities and soil erosion, a large amount of particulate matter and nutrients are discharged into the lake through runoff (Behrenfeld et al., 2013; Siegel et al., 2014). This particulate matter also affects the carbon balance and water quality through decomposition and mineralization (Valier et al., 2015), thus increasing lake eutrophication and causing algal blooms to become a serious environmental problem (Schindler et al., 2008). Quantifying the threat of this foreign matter to lakes' ecology remains a problem. Previous quantitative identifications of organic sources concentrated on lake and marine sediments (Alonso-Hernandez et al., 2017; Wang et al., 2018; Xu et al., 2017), while research on the contribution of organic matter from different sources to POM, especially during cyanobacteria blooms, is still scarce.

Carbon, nitrogen isotopes and the C/N ratio can be used to trace the source of organic matter in large shallow lakes (Meyers, 1994; Niu et al., 2017). The atomic C/N ratio and stable isotopic composition of bulk organic material have increasingly been used to quantify the contribution of several sources of mixed organic carbon in water (Luo et al., 2015; Nienhuis, 1981). In general, based on the different mechanisms of the CO_2 fixation, $\delta^{13}C$ values have been widely used in order to differentiate between terrestrial C3 and C4 plants. C3 plants usually produce −20‰ isotopic fractionation, while C4 plants only produce −7‰ (Meyers, 1997). The $\delta^{13}C$ end-member mixing model resolves the estimation of the contribution of OM to POM from terrigenous and autogenous organic carbon (Calder and Parker, 1968). Meanwhile, macrophytes and phytoplankton also have distinct $\delta^{13}C$ values that reflect the use of atmospheric CO_2 versus dissolved inorganic carbon for photosynthesis (Taipale et al., 2016). On the other hand, the nitrogen (N) uptake pathways of different species also make it possible to employ $\delta^{15}N$ values as a tracer for organic materials. The ratio of phytoplankton and macrophytes in an endogenous material can be quantitatively calculated using an isotope mixing model with $\delta^{13}C$ and $\delta^{15}N$ (Luo et al., 2015). In fact, tracking the sources of POM in lakes remains a challenging task since the isotopic values of different sources may be similar.

It is important to constrain the sources and cycling of POC for fully understanding lake carbon cycle, and migration of contaminants (Chen et al., 2018). However, the sources and cycling of POC in large freshwater lakes in the algal bloom season has not been well delineated until now. We hypothesized that all contributory sources of POM were from algae from algal blooms in Lake Taihu. The purpose of this study was to use bistable isotopes in order to determine the contributions of different endmembers to the POM in algal blooms and to analyse the causes of the endmembers' contributions in different lake regions in combination with environmental factors. These findings can provide a deep understanding of the carbon cycle of eutrophic lakes and provide a reference for the water quality improvement in lake ecosystems.

2. Methods and materials

2.1. Study area

A hydrographic cruise was conducted during May 2018 in Lake Taihu, which is a large, shallow, eutrophic lake (surface water area 2338 km^2 and mean depth 1.9 m) in southern China (Xiao et al., 2017) (Fig. 1). This lake is characterized by decades of eutrophication and summertime cyanobacteria blooms, which have been associated with the rapid development of the surrounding catchment (Jiang et al., 2015). Lake Taihu has a complicated river and channel network; more than 200 rivers empty into Lake Taihu, including 30 main inflow rivers (Du et al., 2017). Most of the water enters the lake from the west and flows towards the east, primarily through the northwestern region of Lake Taihu. The exogenous inputs and the endogenous release of nitrogen and phosphorus nutrients have caused serious eutrophication and a sharp decline in the water quality of Lake Taihu (Hai et al., 2010). According to spatial variation in the aquatic environment, Lake Taihu has been divided into Meiliang Bay, Gonghu Bay, East Taihu, South Taihu, West Taihu and Central Taihu (Fig. 1) (Hu et al., 2010).

2.2. Sampling collection

The field measurements in Lake Taihu included taking 32 samples of the surface water (0–10 cm), which was based on the aggregation of the algal blooms in the upper layer (Deng et al., 2016), while more sampling points were taken in the west in order to better assess the real situation of terrestrial sources (Fig. 1). The vertical sections were 0 cm, 20 cm, 40 cm, 70 cm, and 100 cm and were taken in South Taihu, West Taihu, Central Taihu, and Meiliang Bay (the profile samples are given in Fig. 1); the depth sampling design from the experiment on Chaohu Lake was used as a reference Jing et al. (2017). The profile of the sampling points can help to better observe the effect of the sediment resuspension on the surface. To observe the influence of hydrodynamics on the sources of POM, the vertical sampling point of South Lake Taihu was set at 1.5 km from the estuary (Changdou River), where severe algal blooms occurred on the day of sampling. The geographic distribution of the sampling sites was not uniform, with the largest number of samples being from South Taihu and West Taihu, which experienced frequent algal blooms (Hu et al., 2010). The locations of the samples were accurately recorded using a global positioning system (GPS). A Speedtech SM-5A portable echo sounder measured the water depth at a precision of 0.1 mm. The water samples were stored in PE bottles, kept in ice for transport back to the laboratory and then stored at −2 °C in a freezer until they could be analysed (Zheng et al., 2016). After filtration, the filters and trapped particles were frozen and stored in a freezer. In the laboratory, the samples were dried in a freeze-dryer.

2.3. Laboratory analysis

2.3.1. Bulk parameter (Chl-a, C/N, $\delta^{13}C$, $\delta^{15}N$ and POM) analysis

The water samples were filtered through Whatman GF/F fibreglass filters in order to avoid breaking cells. The filters were preheated at 450 °C in order to reduce the background carbon levels, and their weights were recorded. The laboratory analysis included determining the concentrations of chlorophyll *a* (Chl-a) and POM in the water, and a mass spectrometer was used to measure the total organic carbon (TOC), total nitrogen (TN) and natural abundance of $\delta^{13}C$ and $\delta^{15}N$ in the particulate organic matter. The pigments were extracted using 90% ethanol at 80 °C and were spectrophotometrically analysed in order to obtain the absorption coefficients at 750 nm and 665 nm, and a further calculation determined the Chl-a concentration (Jespersen and Christoffersen, 1987). The total suspended matter (TSM) weight was obtained by subtracting the second weight measurement from the first measurement. The TSM concentration was obtained by dividing the weight by the filtered volume. The filters were then re-combusted at 550 °C for 4 h to remove the organic fraction and weighed again to obtain the inorganic suspended matter (ISM) weight. The POM was the difference between the TSM and the ISM. The samples with acid treatments were washed with distilled water to adjust the pH values (6.0–7.0) and then dried in an oven at 55 °C to eliminate the adverse effects on the detection of $\delta^{13}C$ and $\delta^{15}N$ (Li et al., 2018b). A Thermo Flash Analyzer was used to determine the OC, TN, $\delta^{13}C$ and $\delta^{15}N$ values, with the latter two occurring at standard deviations (n = 6) of less than 0.2‰ ($\delta^{13}C$) and 0.25‰ ($\delta^{15}N$).

The isotopic ratios were reported in parts per mil (‰) as follows:

$$\delta^{13}C \text{ or } \delta^{15}N = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \quad (1)$$

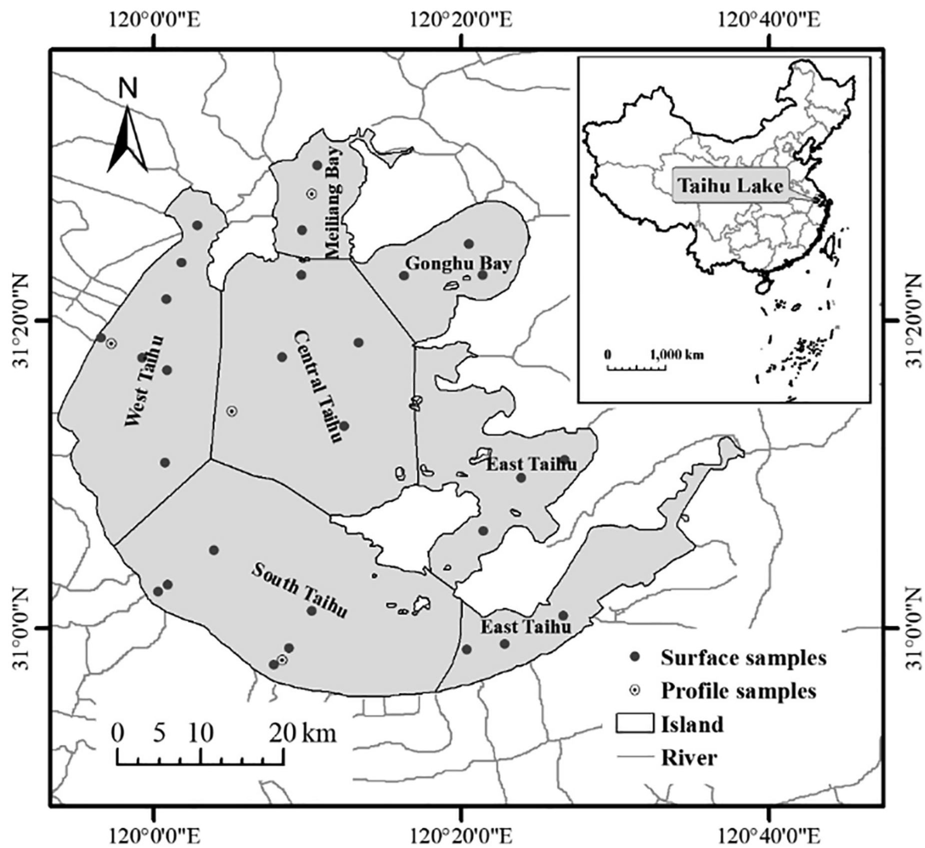

Fig. 1. Geolocations of sample sites in Lake Taihu during measurement campaigns in May 2018. Lake Taihu was partitioned into six sections: Meiliang Bay, Gonghu Bay, East Taihu, South Taihu, West Taihu and Central Taihu (Hu et al., 2010).

where R_{sample} is the isotopic ratio of the sample ($^{13}C/^{12}C$ or $^{15}N/^{14}N$) and $R_{standard}$ is the standard isotopic ratio.

2.3.2. End-member mixing model analysis

The relative contributions of three potential sources (i.e., algal, macrophytal, and terrestrial) to the POM were estimated using Monte Carlo simulations based on three end-member mixing models (EMMs) of the $\delta^{13}C$ and $\delta^{15}N$ ratios. Due to its accurate and stable operations, this method has been successfully applied to the model calculations of the organic carbon sources in marine sediments (Li et al., 2018a; Luo et al., 2015). The simulations were based on the assumption that a given range (mean ± SD) of end-member values ($\delta^{13}C$ and $\delta^{15}N$) for three potential sources approximate a normal distribution, where the mean ± SD value was statistically estimated using the sample data in this study and the previous literature (Andersson, 2011). The isotopic values of the algae, macrophytes and terrestrial POM in Lake Taihu were obtained from a large number of references (Table 1), and their relative contributions were estimated using the following equations:

$$\delta^{13}C_{POM} = f_1\delta^{13}C_T + f_2\delta^{13}C_A + f_3\delta^{13}C_M \quad (2)$$

$$\delta^{15}N_{POM} = f_1\delta^{15}N_T + f_2\delta^{15}N_A + f_3\delta^{15}N_M \quad (3)$$

$$1 = f_1 + f_2 + f_3 \quad (4)$$

where the subscripts POM, T, A and M refer to the POM, terrigenous POM, algae and macrophytes, respectively. f_1, f_2 and f_3 are the relative contributions of terrigenous POM, algae sources, and macrophyte sources to the POM, respectively. The key to solving the EMM model was provided by (Andersson, 2011). The $\delta^{13}C$ and $\delta^{15}N$ values of the POM that were measured in Lake Taihu, as well as the $\delta^{13}C$ and $\delta^{15}N$ values of the algae, macrophytes, and terrestrial POM in Lake Taihu, which were reviewed in the literature, were the input parameters of the EMM model. The values of f_1, f_2 and f_3 that were simulated by the EMM model are shown in Section 3.3.

3. Results

3.1. Spatial distribution of POM

The concentrations of the surface water POM corresponding to each sampling point were plotted in Fig. 2. There was a significant spatial difference in the POM concentrations. They were high in the West and lower in the East. The average concentration of POM in the surface water of South Taihu was the highest, which was followed by Meiliang

Table 1
Carbon and nitrogen stable isotopic ratios (‰) of potential sources in POM of Lake Taihu.

Potential sources	$\delta^{13}C$		$\delta^{15}N$		References
	Mean ± SD	Range	Mean ± SD	Range	
Algae	−24.5 ± 0.8	–	9.5 ± 0.4	–	(Kluijver et al., 2012; Mao et al., 2014; Zeng and Wu, 2009)
Macrophytes	−18.1 ± 0.7	−26.8 to −13.2	6.9 ± 0.3	4.6–25.6	(Jing and Juzhen, 2003; Liu et al., 2015; Mao et al., 2014)
Terrestrial POM	−29.2 ± 1.6	−24.0 to −34.5	3.2 ± 2.0	−2.3 to 8.7	(Zeng and Wu, 2009; Zeng et al., 2008)

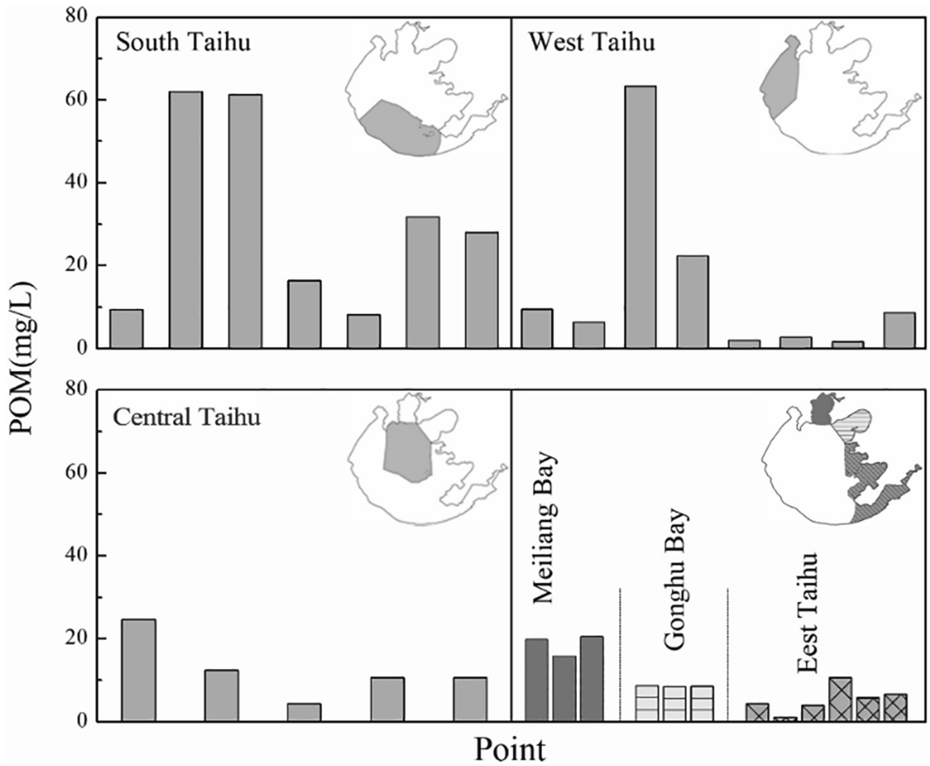

Fig. 2. Variation of POM concentration in surface water in different areas of Lake Taihu. Each column represents the POM concentration of an in situ sampling point.

Table 2
Variation of $\delta^{13}C$, $\delta^{15}N$, TOC, TN, Chl-a and C/N for POM in different lake areas of Lake Taihu.

Area	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	TOC (mg/L)	TN (mg/L)	Chl-a (mg/L)	C/N	n
South Taihu	−23.61 ± 1.95	7.43 ± 2.02	10.43 ± 7.01	4.14 ± 1.46	193.16 ± 177.39	5.18 ± 1.36	7
West Taihu	−25.64 ± 2.35	8.47 ± 1.95	2.79 ± 3.06	3.00 ± 0.74	89.84 ± 162.93	5.86 ± 1.04	8
Center Taihu	−22.76 ± 0.91	8.60 ± 0.99	3.71 ± 2.13	2.63 ± 0.33	66.80 ± 48.17	5.03 ± 0.25	5
Meiliang Bay	−24.04 ± 0.79	10.67 ± 0.38	3.67 ± 1.75	2.48 ± 0.15	100.41 ± 31.18	5.52 ± 0.82	3
Gonghu Bay	−25.57 ± 0.39	9.89 ± 0.22	1.57 ± 0.00	1.69 ± 0.13	16.10 ± 0.41	5.94 ± 0.14	3
East Taihu	−20.32 ± 0.93	37.55 ± 0.55	1.13 ± 0.58	1.97 ± 0.40	19.97 ± 21.58	6.52 ± 0.69	6

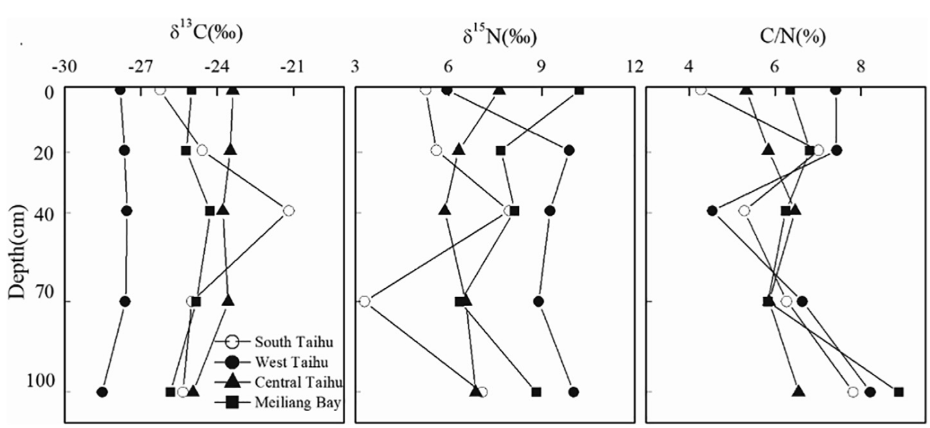

Fig. 3. Depth profiles for $\delta^{13}C$, $\delta^{15}N$ and C/N in South Taihu, West Taihu, Central Taihu and Meiliang Bay. The depths are 0 cm, 20 cm, 40 cm, 70 cm and 100 cm.

Bay and West Taihu, and their values were 31.02 mg/L, 18.74 mg/L and 14.59 mg/L, respectively. The average POM concentrations of Gonghu Bay and East Taihu were small, and both were less than 10 mg/L. South Taihu's POM had the biggest spatial difference where the ratio of the maximum value to the minimum was approximately 37. Similar to South Taihu, the spatial heterogeneity of West Taihu was also significant under the influence of algal blooms. Both the algae reproduction and the POM increased significantly. Conversely, the internal variation of the POM in other areas, such as that of Meiliang Bay, Gonghu Bay and East Lake, was small (Fig. 2). This phenomenon made it easy for algae to be mistaken as the sole source of POM in surface water.

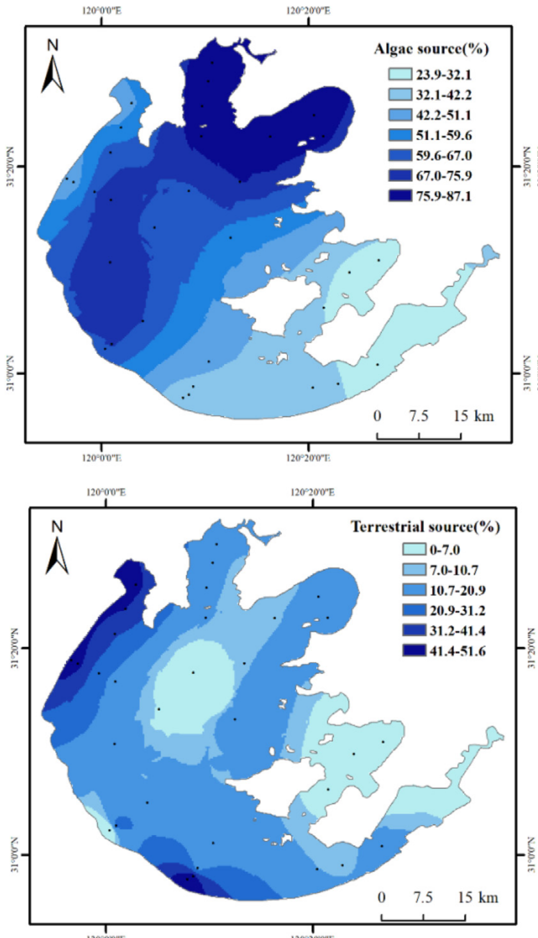

Fig. 4. Kriging interpolation was used to spatially distribute the contribution of algae sources, macrophytes sources and terrestrial sources to POM in the surface waters of Lake Taihu.

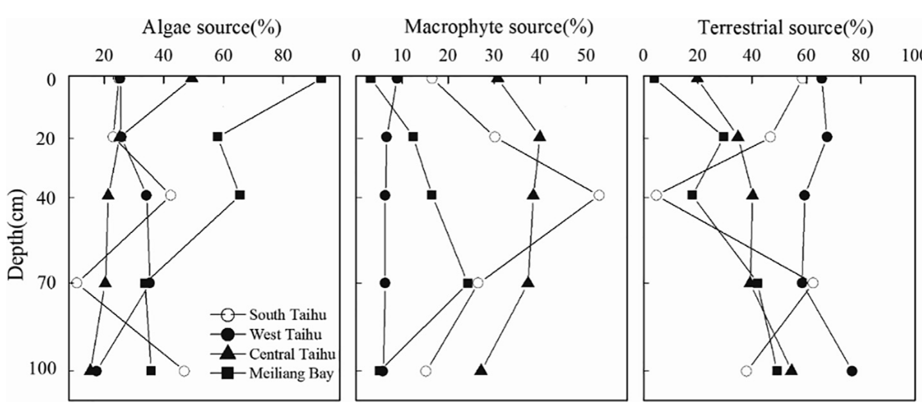

Fig. 5. Different sources of POM on the vertical profile using Monte Carlo simulation of $\delta^{13}C$ and $\delta^{15}N$.

3.2. Stable isotopes of POM

The spatial variations of the $\delta^{13}C$, $\delta^{15}N$, TOC, TN, Chl-a and C/N with respect to the POM of surface water are shown in Table 2. The $\delta^{13}C$ values of the surface water varied from −26.57‰ to −22.18‰ with an average of −24.11‰, indicating the dominance of C3 plants. The value of the isotopic $\delta^{15}N$ showed an extreme spatial heterogeneity ranging from −11.67‰ to −3.03‰. Compared with other regions, the internal differences of the $\delta^{15}N$ values of South Taihu and West Taihu were huge, indicating that there were also large differences in the values of the internal $\delta^{15}N$ between the two regions. Similarly, the values of the TOC, TN, Chl-a and C/N in all regions also showed strong spatial and internal differences. This indicated that the POM composition was complex and the proportion of substances from different sources had spatial variations.

Depth profile analysis was performed in four regions with large differences in their POM concentrations, namely, South Taihu, West Taihu, Central Taihu and Meiliang Bay (Fig. 3). The value of the isotopic $\delta^{13}C$ and C/N decreased as the depth increased, which indicated that the proportion of POM from external sources decreases as the intensity increases (Fig. 3). $\delta^{15}N$ was irregularly distributed vertically, thus reflecting the complexity of the sources of the vertical water POM.

Table 3
Literature data on quantitative estimation of dominant source of organic matter in eutrophic water bodies.

Study site	Research object	Dominant source	Analytical methods	References
Mara and Magu bays (Lake Victoria, Tanzania waters)	Suspended particulate matter	Detritus of aquatic	Isotopic ratios	(Machiwa, 2010)
Lake Dongting and Lake Poyang (China)	POM	Terrestrial organic matter	Carbon isotope	(Bao et al., 2014)
Wilson Inlet (Australia)	Sediments	Microalgae and bacteria	Isotopic ratios lipid biomarkers	(Volkman et al., 2008)
Arcachon Bay (France)	Sediments	Autochthonous sources (81% of potential sources)	Elemental and isotopic ratios	(Dubois et al., 2012)
Lake Taiu (China)	POM	Algae sources (an average of 57.2% of potential sources) 57.2%	Isotopic ratios	This study

3.3. Results of Monte Carlo simulations

From the perspective of the whole lake, the average algal source POM was 57.2%, which was higher in the north than in the south and higher in the west than in the east (Fig. 4). The areas with the highest algal contributions were Meiliang Bay and Gonghu Bay at 89.7% and 86.3%, respectively. The proportions of algal sources in the western estuary area and East Taihu were the smallest with a minimum of 10.8%. The POM derived from aquatic plants was mainly distributed in the eastern part of Lake Taihu, and the contribution rate from east to the west gradually decreased with an average of 24.5%. The terrestrial POM had the lowest ratio with an average of 18.3%, while it was the largest at 72.6% along the West Taihu coast. South Taihu and West Taihu had the highest terrestrial POM averages at 23.7% and 34.5%, respectively. Different sources of POM in the vertical profile are shown in Fig. 5. Except for South Taihu, the results of the vertical section were consistent, i.e., the contribution from algae decreased as the depth increased, and the terrestrial contribution increased with the depth. The results from the four vertical points showed that the contribution rate of algae sources in Meiliang Bay was the highest with an average of 64.6%, and the proportion of terrestrial POM in West Taihu was as high as 65.2%. In terms of the averages, the terrestrial ratio in the vertical profile was greater than that of algal sources and plant sources at 40%, 37.9%, and 22.1%, respectively.

4. Discussion

Due to human activities and climate warming subsequently causing frequent outbreaks of algal blooms in eutrophic lakes, autochthonous sources such as microalgae have proved to be overly abundant in eutrophic lakes. However, our isotopic evidence revealed that algae were not the only source of POM, and external inputs, as crucial contributors, cannot be ignored. Evidence from isotopes suggested that the proportion of algal source POM was 57.2% with the same major source in Wilson Inlet and Arcachon Bay (Table 3). In the traditional organic source evaluation, aquatic plant sources are considered as endogenous or algal sources and neglected, which greatly overestimates the contribution of algae to lake organisms. In this study, the result of the algal source ratio estimation was reliable, and it can also be reflected by the significant positive correlation between POM and Chl-*a* (Fig. 6). The onsite production of phytoplankton was a vital source of POM in lake Taihu because Chl-a can be used to characterize the stock of phytoplankton (Harrison et al., 2015). In addition, the dominant algae species in Lake Taihu is microcystis (Liu et al., 2011), which has a gas vesicle that functions as a buoy. Under the influence of wind, the algae are pushed to the windward shore (Abeynayaka et al., 2017). This was consistent with the higher proportion of algae sources in Meiliang Bay and Gonghu Bay.

The ratios of terrestrial POM in the surface water and vertical section were 18.3% and 40.0%, respectively, and the highest value was 76.8%. The huge proportion was enough to focus our attention on the input of external organic matter. Similar to the study of Dongting Lake and Poyang Lake (Bao et al., 2014), the dominant position of the land in West Taihu and South Taihu attributed to the influx of large amounts of organic matter (Qin et al., 2007). On the other hand, a large amount of terrestrial POM in surface water comes from the replenishment of the sediment resuspension. The results of the four vertical sections showed that in West Taihu, Central Taihu, and Meiliang Bay, the terrestrial POM increased as the depth increased (Fig. 5). The vertical section from South Taihu was too close to the estuary. As a result, it was affected by hydrodynamics, and the proportion of terrestrial POM was chaotic. Low light and nutrient concentrations limit the growth of phytoplankton (Su et al., 2016), resulting in a decrease in phytoplankton in the POM and an increase in the terrestrial sources. In the sediments of Lake Taihu, the proportion of terrestrial organic matter accounted for 66% of all sedimentary organic matter (Xu et al., 2015). When wind speeds exceed

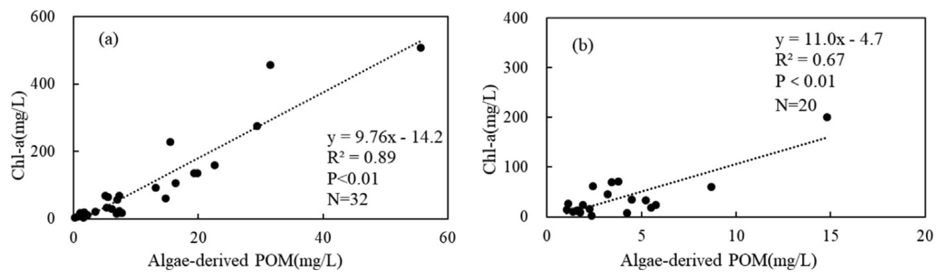

Fig. 6. Relationship between Algae-derived POM and chlorophyll of Lake Taihu, (a) surface water (b) vertical section.

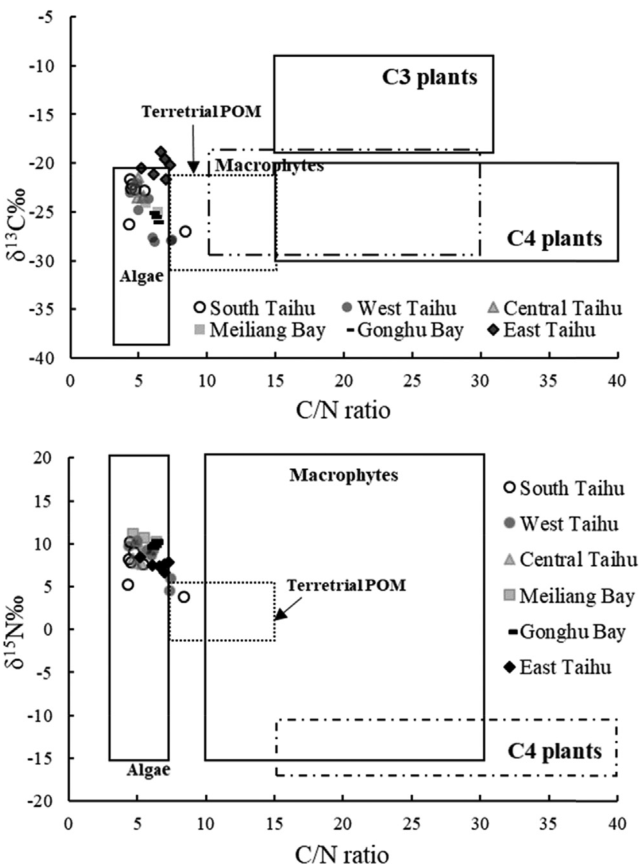

Fig. 7. Comparison of δ^{13}C, δ^{15}N and C/N values for particulate organic matter (POM) in Lake Taihu.

3.7–4.0 m/s, sediment resuspension occurs (Sha-sha et al., 2015), and the terrestrial POM deposits in the sediment that replenishes the upper water. Hydrodynamic conditions change the proportion of different sources, and the POM that is generated by resuspension re-enters the biopump cycle.

In eutrophic lakes, aquatic macrophytes are generally rich in organic carbon compounds such as proteins, lipids, and carbohydrates (Bertilsson and Jones, 2003), which are also internal sources of POM (Bertilsson and Jones, 2003). In this study, the distribution of the biomass of macrophyte-derived POM in Taihu Lake was almost identical. The vegetation coverage of East Taihu is 95% (Qin et al., 2007), thus making it contain the highest proportion of macrophytes sources. Under the action of microorganisms, most of the carbon, nitrogen and phosphorus elements in plants are released into the water through the dissolution of plant tissues, and some of these are in the form of POM. The nutrients that are released during the decomposition of plants promote the growth of algae, which in turn lead to an increase in the proportion of algae in POM. In other studies, both the in situ aquatic vegetation and the external input of rivers affect the proportion of lake organic matter (Table 3). Others inconsistent findings with respect to the quantitative estimation of the POM sources are likely due to the different environmental conditions (e.g., the water quality, primary production, river inflow, water depth, and abundance of microorganisms) for organic matter accumulation.

C/N, δ^{13}C, and δ^{15}N can be respectively used to study the sources of organic matter, but the one-factor evaluation tends to neglect the contribution of aquatic vegetation, thereby resulting in a great overestimation of the proportion of algae sources. In general, terrestrial plants with more lignin and cellulose are relatively low in nitrogen and therefore have higher C/Ns. The C/N of fresh algae is between 3 and 8 (Meyers, 1994), and the range of C/N in Lake Taihu was 4.3–8.4, which indicated that there was a terrestrial and spontaneous mixture of POM in the surface water of Lake Taihu. Furthermore, the mean value of C/N was 5.7, thus indicating that the POM was mainly derived from authigenic algae. However, the overlap of the C/N values of large plants and terrestrial POM makes them difficult to distinguish (Fig. 7). The amount of δ^{13}C that was measured in the surface water of Lake Taihu was −28.0‰ to 18.9‰, thereby indicating that the POM composition of Lake Taihu was under the joint influence of terrestrial and endogenous organic matter (Table 3). According to the different photosynthesis pathways, terrestrial plants can be divided into C3 and C4 plants (Lopes et al., 2013). The δ^{13}C values of the C3 plants were between −20‰ and −30‰, the δ^{13} C values of the C4 plants were between −19‰ and −9‰(Fig. 7), and the δ^{13} °C values of the CAMs were between −30‰ and −10‰. The endogenous organic matter δ^{13}C is between −19‰ and −22‰; if the δ^{13}C is between −22‰ and −16‰, it is considered to be a mixture of terrestrial and aquatic sources (Emerson and Hedges, 1988). For lakes that are dominated by autogenous organic matter, phytoplankton has lower carbon isotopic values than submerged plants (Han and Dickman, 1995). Because phytoplankton prefers ^{12}C-rich CO_2 in the air during light and photosynthesis, the amount of δ^{13}C decreases, and submerged plants are relatively positive with respect to carbonate, dissolved CO_2, and δ^{13}C. δ^{15}N can also be a source of organic matter in lakes due to nitrogen being fixed differently in terrestrial and aquatic systems (Han and Dickman, 1995). The δ^{15}N values of the POM in the surface water of Lake Taihu ranged from 3.9‰ to 11.1‰. They were very close to the average values of algae, thus indicating that the algae in Lake Taihu were the primary source of POM (Fig. 7). It is generally believed that the average value of terrestrial δ^{15}N is approximately 2‰, the average value of algae δ^{15}N is approximately 8‰, and the plankton δ^{15}N value is larger than that of large aquatic plants (Emerson and Hedges, 1988). In summary, although both C and N isotopes can characterize the sources of POM, the combination of the two can provide higher accuracy and distinguish more sources.

In general, algae are more likely to decompose than plants and exogenous organisms and then release nutrients (Hałemejko and Chróst, 1984), which is one of the self-sustaining mechanisms of algal blooms (Hudson et al., 1999). As the climate warms, the algal blooms become more intense (Qin et al., 2010), and the proliferation of microcystis further changes the proportion of algae-derived POM. Meanwhile, rainfall also carries a large amount of terrestrial POM that

compresses the space of endogenous organic matter. The current lake governance is focused on algal blooms and has taken various measures such as aeration, dredging, deep water discharge, macrophyte removal, etc. However, the input of exogenous organic matter often increases the large amounts of nutrients and some other pollutants, which cause great difficulties for the treatment of lakes. Therefore, exogenous control cannot be ignored during the outbreak of algal blooms.

5. Conclusion

The combination of δ^{13}C and δ^{15}N showed that algae were not the only source of POM during the algal bloom season. Analysis involving algae sources, macrophytes sources, and terrestrial sources can correct the overestimation of algal sources. Although the proportion of algae-driven POM in the whole lake was 57.2%, the terrestrial POM still dominated in the coastal areas of West Taihu and South Taihu. The contribution ratio of different endmembers to POM was calculated, in which algal-source POM was the highest, followed by macrophyte-source and terrestrial-source. The proportion of algae-derived POM was affected by the cyanobacterial biomass, the nutrients and meteorological elements, which cause seasonal changes. Additionally, as the water depth increased, the proportion of algal sources will be weakened by the proportion of terrestrial sources. The terrestrial-derived POM was affected by the distribution of rivers, primarily in South Taihu and West Taihu. Resuspension caused by hydrodynamic conditions increased the contribution of terrestrial sources in the sediment to the surface water. Affected by the placement of vegetation in Lake Taihu, the POM of aquatic plants was mainly concentrated in East Taihu. As the climate warms, the algal blooms become more intense, and the proliferation of microcystins further changes the proportion of algae-derived POM. Furthermore, the increase in the exogenous POM that is caused by summer rainfall will deteriorate the progress of exogenous organic pollutants. These results provide an important reference for the decline of eutrophic lake ecosystems, carbon cycles and lake management.

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